Determining Moisture Content in Small Wheat Samples by Dual-Frequency RF Impedance Sensing

C. V. K. Kandala, S. O. Nelson, K. C. Lawrence

Abstract. *A technique is described for estimating moisture content of small samples of hard red winter wheat (10 to 30 kernels) by impedance measurements at 1 and 4.5 MHz on a parallel-plate capacitor holding the sample between the plates. The measurement system was calibrated by measurements on samples, ranging from 9 to 20% moisture content, wet basis, from three wheat cultivars grown in 1991 and 1992. Validation measurements were taken for prediction of moisture content of small wheat samples from three different cultivars harvested in 1992. Moisture contents of the small samples were predicted with a five-variable equation involving differences in the real and imaginary components of the complex impedance at the two frequencies. The standard error was 0.9% moisture content. The study established a basis for further development of the rapid, nondestructive method for estimating moisture content of small wheat samples.*
Keywords. *Moisture content, Wheat, Kernels, Measurement.*

Moisture content* in cereal grains is the most important factor determining suitability for storage, transport, milling, and other processes. Knowledge of grain-lot moisture contents is also very important whenever grain is traded, not only for the reasons stated, but also because the moisture level influences the trading price. Moisture content affects the economic value of grain lots because of drying costs, if moisture content is above safe storage levels, and because of the "shrinkage" that takes place when the moisture content is reduced. Loss in weight because of moisture driven off when grain is dried must be taken into account in determining the fair market value.

Because of the universal need for reproducible moisture content information on grain lots, standard moisture testing procedures have been developed. These methods generally involve oven drying of small samples at specified temperatures for specific time periods (ASAE, 1994) and require special laboratory equipment and procedures that are time consuming and relatively expensive because of skilled labor requirements. For these reasons, electrical and electronic moisture meters have been developed that provide rapid estimates of grain sample moisture contents approximating those of the standard reference methods. These kinds of moisture testers for grain have evolved over many years.

A logarithmic relationship between the electrical dc resistance of bulk samples of grain and their moisture contents was reported by Briggs (1908). About two decades later, successful measurement of grain moisture content with radio-frequency (RF) instruments was reported by Berliner and Rüter (1929) and Burton and Pitt (1929). A review of the subsequent development of electrical grain moisture meters has been published (Nelson, 1977). The sensing of moisture content by most electronic type moisture testers depends on the high correlation between the moisture content of grain and its dielectric properties. The constitutive parameters or properties of interest are incorporated in the complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$, where the real component, ε', is proportional to the dielectric constant, and the imaginary component, ε'', is proportional to the dielectric loss factor (Nelson, 1973, 1991).

Because of the high correlation between dielectric properties of grain and its moisture content, these properties can also be used for sensing the moisture content of individual grain kernels. The RF impedance of a small parallel-plate capacitor holding the kernel between the plates can be measured at two frequencies and used to provide relatively accurate values for the moisture content of individual corn kernels (Kandala et al., 1989). The technique has also been used to determine the moisture content of single kernels of popcorn (Kandala et al., 1992) and was later extended to measurements on small samples (15 to 30 kernels) of popcorn (Kandala et al., 1994).

In addition to requiring only very small samples of the grain, these measurements require no volume or weight determinations on the sample. Therefore, they can be made extremely quickly and they are nondestructive as well. There may be applications where moisture determination on such small samples of wheat would be advantageous. For example, the technique could provide more information on the variability of moisture content in samples than the single measurement of mean moisture

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* Moisture contents through this article are expressed in percent, wet basis.

content for the entire sample, and it could provide that information much more rapidly than a single-kernel tester. The purpose of this article is to report measurements achieved on such small samples of hard red winter wheat.

Materials and Methods

Basic Principles

The capacitance C of a parallel-plate capacitor with two plane-surface electrodes of equal area, filled with a homogeneous dielectric of permittivity ε, is given by:

$$C = \frac{\varepsilon A}{d} \qquad (1)$$

for $d << A$, where A is the area of one of the plates, and d is the distance of separation between the plates. The relative permittivity ε_r is defined as $\varepsilon_r = \varepsilon/\varepsilon_0$, where ε_0 is the permittivity of free space. In general, ε_r is a complex quantity and is expressed as $\varepsilon_r = \varepsilon'_r - j\varepsilon''_r$, where ε'_r and ε''_r are the dielectric constant and loss factor, respectively. For a series equivalent RC circuit (fig. 1), the dissipation factor D, or loss tangent, is related to the dielectric constant and loss factor as $D = \tan\delta = \varepsilon''_r/\varepsilon'_r$, where δ is the loss angle of the dielectric. The dissipation factor is related to the phase angle θ between the applied ac voltage V and the current I through the circuit, which is the complement of δ, as $\theta = \tan^{-1}(1/D)$. The impedance of the series equivalent circuit can be expressed as $Z = R + jX$, where R is the series resistance and X is the series reactance due to the series capacitance C. In this case, $X = -1/(\omega C)$.

When a few kernels are placed between the parallel-plate electrodes, they do not occupy the entire space and equation 1 does not apply, but the capacitance of the parallel-plate system with the kernels as a dielectric will provide information about the influence of the kernels on the measured values. Thus, the effects of the kernels on the measured value of impedance can be used to predict the moisture content of the kernels.

To compensate for the influence of variations in kernel shape, number of kernels, the volume they occupy between the plates, and plate separation, impedance measurements can be made at two frequencies, and the differences in the values of the impedance or its related variables at the two frequencies can be used to estimate the moisture content of the kernels independent of those variations. This has been possible with similar measurements on single corn kernels (Kandala et al., 1989, 1992) and small samples of popcorn (Kandala et al., 1994).

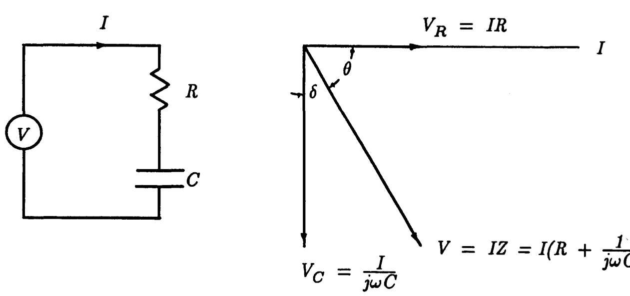

Figure 1–Series equivalent circuit representation and associated phasor diagram.

Wheat Lots

Six lots of hard red winter wheat, *Triticum aestivum* L., were used for these tests. All were obtained as cleaned lots of Certified Seed from the Nebraska Foundation Seed Division, Lincoln. Seed lots of the cultivars 'Redland' and 'Siouxland' were harvested in 1991, and those of 'Arapahoe', 'Buckskin', 'Centura', and 'Karl' were harvested in 1992. All lots had been stored since shortly after harvest at 4°C and 40% relative humidity. To obtain moisture contents higher than 13%, wet basis, distilled water was added to sublots that were then sealed in glass jars and allowed to equilibrate for several weeks at 4°C. To obtain moisture contents below about 13%, moisture was removed from sublots by drying them in a forced-air oven at 55°C. Thus, six moisture content levels, ranging from about 9 to 20%, were provided for the measurements on each of the six lots. Moisture contents of subsamples used for the impedance measurements were determined by oven drying triplicate samples of 10 g each for 19 h at 130°C in disposable aluminum dishes (ASAE, 1994). Samples from the oven were cooled in desiccators over anhydrous $CaSO_4$ before final weighing to determine moisture loss.

Equipment

Measurements on small samples of wheat (about 10 to 30 kernels) between the parallel plates were taken with a Hewlett-Packard 4192A LF Impedance Analyzer equipped with a 16096A Test Fixture and a specially constructed parallel-plate electrode assembly (Kandala et al., 1989). The electrode assembly was equipped with two 50-mm-diameter circular brass plates for the electrodes (fig. 2). The wheat kernels rested on the lower plate, and a 1-mm-thick Plexiglas ring with an inner diameter of 40 mm, fitted to the lower plate, kept the kernels from extending to the edges of the plate. The upper plate was maintained in contact with the kernels by the spring pressure of a Starrett No. 25-881 dial indicator gauge used only for convenience. The measurements were computer controlled and data were collected from the impedance analyzer and a Mettler AE 163 electronic balance used to weigh samples for the oven moisture tests. Impedance values were recorded in ohms. Capacitance values were recorded in picofarads to three decimal places, dissipation factor to four decimal places, and phase angle in degrees to two decimal places, as given by the impedance analyzer. Weights of the small samples were recorded in grams to four decimal places.

Procedures

Samples of the Arapahoe, Redland, and Siouxland cultivars were selected as the calibration set for the small-sample measurements, providing some diversity in both cultivar and year of harvest (1991 and 1992). Samples of the 1992 Buckskin, Centura, and Karl cultivars were selected as the validation set. Sublots of the six wheat cultivars, conditioned to the different moisture levels, were allowed to reach room temperature (24°C) in sealed jars prior to the measurements. Upon raising the upper plate electrode, enough kernels were placed on the lower plate to loosely occupy the space within the plastic ring, more or

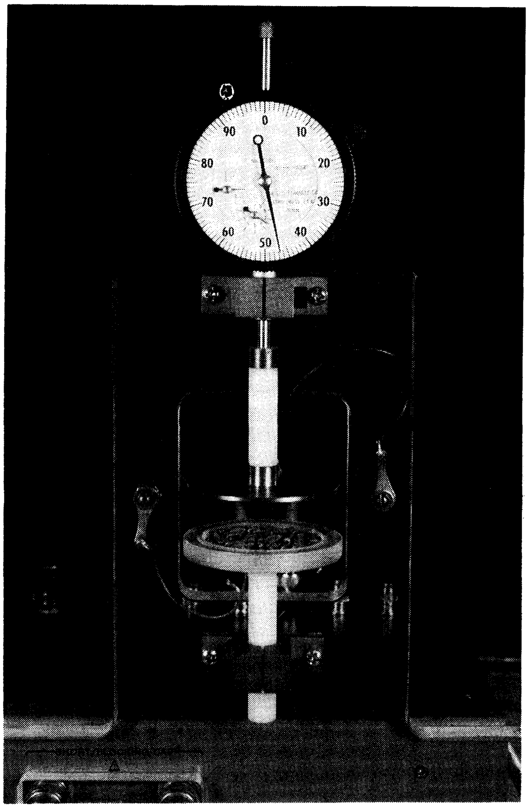

Figure 2–Parallel-plate electrode assembly with 50-mm-diameter electrodes and Plexiglas ring for small wheat sample containment.

less, and the upper plate was then released to rest on the kernels. Impedance measurements with an oscillator level of 1.0 V, requiring about 3 s, were taken for this small sample at 1 and 4.5 MHz. This procedure was repeated for 9 more small samples from this sublot and for 10 small samples from each remaining sublot of this cultivar and all moisture sublots of the other cultivars in the calibration set. Random variation in sample size was permitted for the 10 samples measured from each sublot. Three 10-g samples of each sublot were taken and sealed in small sample jars at the time of measurement for the oven moisture determinations. Identical procedures were followed for measurements on the six sublots of the three cultivars in the validation set.

Analysis of Measurement Data

Values of C, D, $|Z|$, and θ were obtained by the impedance analyzer at frequencies of 1 and 4.5 MHz for small wheat samples. Files included these data for each of 10 samples at each of six different moisture levels for each of the six cultivars. Therefore, measurements were taken on a total of 360 samples. Moisture contents determined from oven tests ranged from about 10 to 22%. Electrical measurement variables that were useful in predicting corn kernel moisture contents from similar measurements on individual kernels (Kandala et al., 1989) and on small popcorn samples (Kandala et al., 1993) were considered for predicting moisture contents of the small wheat samples. These included $\Delta C = C_1 - C_2$, $\Delta D = D_1 - D_2$, and $\Delta\theta = \theta_1 - \theta_2$, where subscripts 1 and 2 refer to the 1- and 4.5-MHz frequencies, respectively, at which measurements were taken.

Additional variables were considered in combinations that were relevant to the series-equivalent RC-circuit mode of measurement (fig. 2) and used in the PROC REG program (SAS Institute, 1985) to identify the most useful variables and combinations of the variables for reliable prediction of small wheat sample moisture content. The components, R and X, of the impedance, $Z = R + jX = R + 1/j\omega C$ were included as R_1, R_2, X_1, X_2, $\Delta R = R_1 - R_2$, and $\Delta X = X_1 - X_2$.

Other terms included were ΔC, $(\Delta C)^2$, and $[\Delta\theta/(\Delta C - K\Delta D) - \Delta\theta\cdot\Delta C]$, which was similar to an important variable in the equation for estimating moisture content of single corn kernels and small popcorn samples (Kandala et al., 1989, 1993).

Results and Discussion

Impedance measurements taken on small samples from the three calibration lots, along with their moisture contents from the oven tests, were used to obtain regression equations for moisture content prediction. The prediction equation developed included five variables which were chosen on the basis of statistical significance and their theoretical physical significance. For example, ΔC relates to the dielectric constant, and ΔD relates to the loss tangent, both of which are closely related to moisture content. Selection of both ΔR and ΔX in the same equation also insures that functions of both the real and imaginary parts of the permittivity are represented. The developed equation is as follows:

$$M = 38.50 + 0.0489\,\Delta R - 0.00279\,\Delta X - 77.28\,\Delta C$$

$$+ 52.44\,(\Delta C)^2 - 0.0395[\Delta\theta/(\Delta C - K\Delta D) - \Delta\theta\cdot\Delta C]$$

$$r^2 = 0.933 \qquad (2)$$

where R and X are expressed in ohms, C is in picofarads, θ is in degrees, D is dimensionless, K is a constant for dimensional compatibility with a numerical value of 4 selected for these analyses, and r^2 is the coefficient of determination.

The standard error of calibration (SEC)* for equation 2 was 0.879% moisture content. The calibration data are shown in figure 3. This SEC value and the r^2 of 0.93 compare to values of 0.63 and 0.64% and 0.97 and 0.98% for small samples of popcorn (Kandala et al., 1994) and

$$* \quad SEC = \left(\frac{1}{n-p-1}\sum_{i=1}^{n} e_i^2\right)^{1/2}$$

where n is the number of observations, p is the number of variables in the regression equation with which the calibration is performed, and e_i is the difference between the observed and reference value for the *ith* observation.

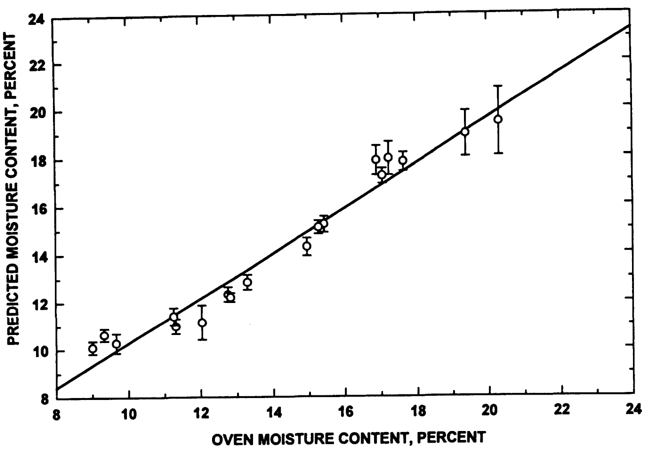

Figure 3–Calibration data for moisture determination in small samples (10 to 30 kernels) of Arapahoe, Redland, and Siouxland hard red winter wheat by dual-frequency RF impedance measurements (eq. 2). Error bars represent ± one standard deviation.

single kernels of popcorn (Kandala et al., 1992), respectively.

Moisture contents of small samples from the Buckskin, Centura, and Karl lots, calculated by equation 2, were predicted with a standard error of prediction (SEP)† of 0.907% moisture content. A plot of these predictions is shown in figure 4. This SEP value compares with 0.68% and 0.56% for small samples of popcorn and single kernels, respectively. Although a little less accurate for the small wheat samples, the technique shows promise as a rapid nondestructive means for estimating moisture contents of small samples to within less than 1% moisture content similar to results obtained earlier on single kernels of grain (Kandala et al., 1989, 1992) and small samples of popcorn (Kandala et al., 1994). The accuracy of the technique appears to deteriorate at high moisture levels, as do other electrical moisture sensing methods. Common electrical moisture meters using larger samples have better accuracies (Nelson, 1977; Hurburgh et al., 1987), but the technique described here does provide nondestructive moisture estimates for very small samples.

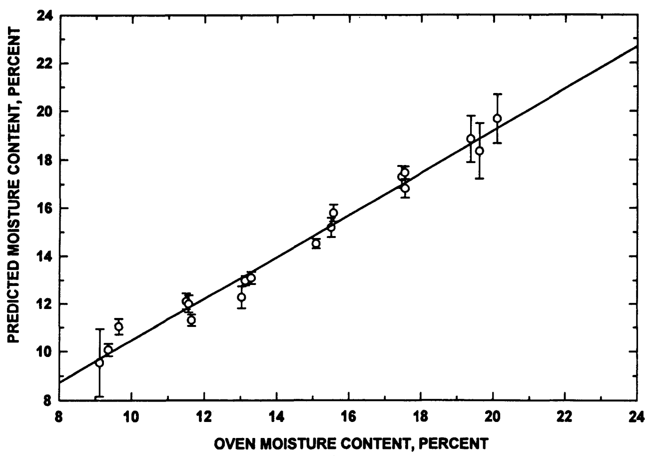

Figure 4–Moisture content predictions for small samples (10 to 30 kernels) of Buckskin, Centura, and Karl hard red winter wheat by dual-frequency RF impedance measurements and equation 2. Error bars represent ± one standard deviation.

† $\mathrm{SEP} = \left[\frac{1}{n-1}\sum_{i=1}^{n}(e_i - \bar{e})^2\right]^{1/2}$

where n is the number of observations, e_i is the difference in the moisture content predicted and that determined by the reference method for the *ith* sample, and $\bar{e}$ is the mean of e_i for all of the samples.

Conclusions

Complex impedance measurements at two frequencies, 1 and 4.5 MHz, on small samples of hard red winter wheat (10 to 30 kernels) held between the parallel plates of a capacitor, can be used to estimate quickly the average moisture content of the kernels. The method is nondestructive and rapid, because no weight or volume measurement is required for the sample. The standard error in predicting moisture contents was less than 0.9% moisture content in validation tests on three wheat lots. Further testing of the method is advisable, but the study provides a basis for further development of the technique for rapid, nondestructive moisture tests on small samples.

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